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Water Quality Improvement through Bioretention: Lead, Copper, and Zinc Removal

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ABSTRACT: Intensive automobile use, weathering of building materials, and atmospheric deposition contribute lead, copper, zinc, and other heavy metals to urban and roadway runoff. *Bioretention* is a low-impact-development best management practice that has the potential to improve stormwater quality from developed areas. The practice represents a soil, sand, organic matter, and vegetation-based storage and infiltration facility used in parking lots and on individual lots to treat runoff. Investigations using pilot-plant laboratory bioretention systems and two existing bioretention facilities documented their effectiveness at removing low levels of lead, copper, and zinc from synthetic stormwater runoff. Removal rates of these metals (based on concentration and total mass) were excellent, reaching close to 100% for all metals under most conditions, with effluent copper and lead levels mostly less than 5 μg/L and zinc less than 25 μg/L. Somewhat less removal was noted for shallow bioretention depths. Runoff pH, duration, intensity, and pollutant concentrations were varied, and all had minimal effect on removal. The two field investigations generally supported the laboratory studies. Overall, excellent removal of dissolved heavy metals can be expected through bioretention infiltration. Although the accumulation of metals is a concern, buildup problems are not anticipated for more than 15 years because of the low metal concentrations expected in runoff. *Water Environ. Res.*, **75**, 73 (2003).

KEYWORDS: stormwater, runoff, bioretention, metals, best management practice, low-impact development.

Introduction

Water quality from nonpoint sources continues to receive greater scrutiny as point discharges are addressed and total maximum daily load regulations in the United States are enforced. Runoff from urban areas is of particular interest because of increased pressures to develop land at greater distances from existing cities and urban centers. Developed land increases impermeable surface, and the inclusion of roads and driveways, various buildings and structures, and managed lawns create higher flows and contribute myriad pollutants to stormwater runoff (Barrett et al., 1998; Sansalone and Buchberger, 1997; Wu et al., 1998). Heavy metals are of particular concern because of their toxicity and persistence. Metals are contributed to urban runoff by automobiles (from the wearing of brakes and tires and various fluid leaks), buildings (weathering of paints and metal components), and atmospheric deposition (Davis et al., 2001a).

Proper control and management of runoff from impervious urban sources can provide for significant improvements to the quality of water entering local waterways. Concern for urban water quality improvements has spawned interest in natural-based treatment processes such as bioretention and vegetated swales (Davis et al., 2001b; Rushton, 2001; Yu et al., 2001). These practices are part of an integrated paradigm known as *low-impact development* (LID) (DER, 1997), which uses vegetated techniques to hold and treat runoff water at the source, maximize infiltration, and reduce both quality and quantity effects on local ecology. Bioretention is a mulch, soil, and plant-based stormwater LID best management practice (BMP). Water quality improvement occurs through bioretention via evapotranspiration, soil filtering, adsorption, and biotransformation mechanisms. To compensate for limited performance data and mechanistic understanding, bioretention design criteria have emphasized increasing depth to increase the likelihood of pollutant attenuation or transformation. Recently, laboratory and pilot-scale bioretention box studies were completed to quantify pollutant removal in bioretention (Davis et al., 2001b). Measured removals of copper, lead, and zinc were excellent (typically greater than 95%). Good removal of total phosphorus (approximately 80%), total Kjeldahl nitrogen (50 to 75%), and ammonium (60 to 80%) were also found. Nitrate removal was poor, with indications of some nitrate synthesis in the systems. Overall, these studies have provided "proof of concept" for bioretention as an effective practice for improving the quality of urban stormwater runoff.

Nonetheless, many demands are placed on stormwater management practices that can render them ineffective or make their use, maintenance, or both cost-prohibitive. The goal of this work was to investigate and evaluate the removal of heavy metals in bioretention. Metals are of particular concern because of possible buildup within treatment facilities and questions about their long-term fate. Bioretention facilities are exposed to a broad array of operating situations, including variable flow and input water quality characteristics. This work examines some of these parameters, specifically water pH, varying pollutant concentrations, and different flow intensity and duration on the pollutant removal characteristics of bioretention. This is accomplished by focusing on the removal of copper, lead, and zinc as representative heavy metals using constructed bioretention boxes under controlled conditions. The results of these environmental variations are compared to previously published data collected under fixed conditions (Davis et al., 2001b).

This work also describes two field-scale investigations. A synthetic runoff was applied to two existing bioretention facilities under controlled conditions and pollutant levels were monitored in effluent underdrains. Metal results are compared to the laboratory results, with a focus on examining the effect of facility depth. Finally, metal removal results are discussed in terms of long-term issues of heavy-metal accumulation and buildup in bioretention and possible strategies to address these issues.

Table 1—Target chemical makeup of water applied as synthetic runoff to bioretention systems.

Pollutant	Chemical	Concentration (mg/L except for pH)
Heavy metals		
Copper	Cupric sulfate ($CuSO_4$)	0.08
Lead	Lead chloride ($PbCl_2$)	0.08
Zinc	Zinc chloride ($ZnCl_2$)	0.6
Dissolved solids	Calcium chloride ($CaCl_2$)	120
pH	Hydrochloric acid/sodium hydroxide (HCl/NaOH)	7.0
Nutrients		
Nitrate	Sodium nitrate ($NaNO_3$)	2 (as N)
Organic nitrogen	Glycine	4 (as N)
Phosphorus	Dibasic sodium phosphate (Na_2HPO_4)	0.6 (as P)

Methodology

Bioretention Box Experiments. Davis et al. (2001b) described experimental procedures for bioretention box studies. Briefly, a small bioretention prototype box (107-cm long × 76-cm wide, with a depth to hold 61 cm of media plus a 15-cm freeboard) and a large box (305-cm long × 152-cm wide, with a depth to hold 91 cm of media plus a 15-cm freeboard) were constructed. Perforated polyvinyl chloride (PVC) pipes were installed at two depths in the small box and three depths in the large box to collect samples for water quality analysis. Each box was filled with a sandy loam soil and topped with a 2.5-cm layer of mulch. Six creeping juniper plants with 13- to 18-cm-long branches were installed in the small box; 12 small creeping juniper plants with 13- to 18-cm-long branches and 12 large creeping juniper plants with branches up to 38 cm were established in the large box.

Dechlorinated tap water was used to prepare synthetic stormwater runoff, with target pollutant levels presented in Table 1. The use of tap water produced some variability in influent pollutant levels, but was necessary because of the large volumes used. Although all experiments contained nitrogen and phosphorus compounds, this study presents and discusses only the metals results.

The synthetic runoff was applied at a standard rate of 4.1 cm/h for 6 hours to each box prototype. At selected time intervals, infiltrated water samples were collected from the lateral ports. The bottom ports were always open; the upper ports were opened only for sampling. In all runs, samples were taken from the input and various outputs throughout the duration of the experiment. To investigate different operating conditions, the flow duration, or rate, or the chemical makeup was varied. In all cases, only one condition was varied at a time. Two or three repetitions were completed on the boxes for each condition. All data from these repetitions were combined to obtain mean influent concentrations, mean effluent concentrations, and concentration reductions for the bioretention treatments. Flowrates were measured and infiltrated volumes were estimated for use in pollutant mass balance calculations.

Field Experiments. The hydraulic loading in both field studies was also fixed at 4.1 cm/h for a 6-hour duration and the target water quality was that of Table 1. The first field study was conducted at a facility that was constructed in 1992 at a shopping mall parking lot in Greenbelt, Maryland. These bioretention cells were covered with approximately 5 cm of mulch and held a thick growth of grasses (90- to 120-cm tall) mixed with a few shrubs and small trees (Figure 1a). A 15-cm (in diameter) perforated PVC pipe was located at a depth of 114 cm to collect infiltrated runoff.

The outlet of this pipe opens into a manhole, which feeds into a large storm sewer pipe.

The Greenbelt investigation was completed in June 1997. Antecedent rain occurred 4 days earlier; the underdrain pipe and manhole were damp. An area approximately 5.3 m^2 (2.3 × 2.3 m) within one of the bioretention cells was boxed off with sandbags adjacent to the manhole. Using a peristaltic pump, 1200 L of the synthetic stormwater runoff was pumped through plastic tubing to the selected area at a flowrate of 2.8 L/min. Flow appeared from the underdrain, and the first sample was taken from the effluent after 15 minutes. Grab samples were collected every 25 to 30 minutes in 125- or 1000-mL bottles, along with selected input samples.

The second experiment was completed in June 1999 at a county facility in Largo, Maryland. This system, which was installed approximately 1 year earlier, was retrofitted into an existing curbside inlet at a parking island (Figure 1b). The media consisted of 50% construction sand, 20 to 30% leaf mulch, and 20 to 30% topsoil. A 15-cm T-shaped underdrain runs the span of the entire system, branching to the inlet at a depth of 128 cm. Bare mulch made up most of the surface, with some grasses, bushes, and small trees. An area that encompassed 2.1 × 2.4 m was cordoned off for runoff application in the center of the facility.

The procedure of this study was identical to that of the Greenbelt experiment. The runoff was initially applied over the entire selected area, but later was focused at a single point in the center of the facility to encourage flow into the underdrain. The soil was extremely dry. Although rain had not occurred for several days, the facility was frequently watered.

Effluent water flow from the Largo facility did not originate from the underdrain. Rather, a pool began to form 3 hours after the onset of the experiment near a crack in the floor of the storm drain invert. Grab samples were collected from this pool every 30 minutes. In both field studies, all samples were collected in acid-washed plastic bottles and transported to the Environmental Engineering Laboratory at the University of Maryland, College Park.

Analytical Methodology. The collected samples were analyzed for copper, lead, and zinc as previously described (Davis et al., 2001b). The metal analyses were completed using an atomic absorption spectrophotometer (model 5100 ZL, Perkin-Elmer, Shelton, Connecticut). The flame module was used for zinc analysis; copper and lead measurements used the furnace module. For the Largo study, both dissolved and total metals were determined, the former by filtering (0.24 μm) before acidification. The practical quantitation limit for copper and lead was 2 μg/L; that for zinc

a. Greenbelt, June 1997

b. Largo, June 1999

Figure 1—Field bioretention facilities: (a) Greenbelt, June 1997 and (b) Largo, June 1999.

Table 2—Summary of metal removal for boxes at different durations and flowrates.

	Standard flowrate and duration, 6 hours, 4.1 cm/h (Davis et al., 2001b)			3-Hour duration		
	Cu (μg/L)	Pb (μg/L)	Zn (μg/L)	Cu (μg/L)	Pb (μg/L)	Zn (μg/L)
I. Small box[a]						
Input	140 ± 32	61 ± 3	600 ± 8	91 ± 22	51 ± 21	630 ± 19
Average ± standard deviation						
U	12 ± 3.4	2.9 ± 1.2	45 ± 13	10 ± 3.1	4.0 ± 1.9[b]	62 ± 26[b]
L	3.8 ± 1.4	<2	<25	3.2 ± 2.0	<2	<25
Removal (%)						
U	91 ± 2	95 ± 2	93 ± 3	89 ± 3	92 ± 5	90 ± 5
L	98 ± 1	>97	>96	96 ± 2	>96	>96
Mass removal (%)	99	>99	98	99	99	99
II. Large box[a]						
Input	64 ± 5	54 ± 6	590 ± 37	–	–	–
Average ± standard deviation						
U	7.4 ± 3.5	5.0 ± 5.7	68 ± 87	–	–	–
M	4.5 ± 1.9	<2	<25	–	–	–
L	4.9 ± 1.8	<2	<25	–	–	–
Removal (%)						
U	89	92	88	–	–	–
M	93	>98	>98	–	–	–
L	92	>98	>98	–	–	–
Mass removal (%)	>99	>99	>99	–	–	–

[a] U = upper ports, M = middle ports, and L = lower ports.
[b] t test indicates significantly different from standard conditions at 95% confidence level.
[c] Second number considers mass lost due to "bypass" in experiments where head was greater than approximately 16 cm; see text for details.

was 25 μg/L. Data below the quantitation limit were estimated by fitting a log-normal distribution to the valid data and extrapolating for the lower points (Helsel, 1990). Statistical significance in comparing various effects was evaluated using the Student's t test and a 95% confidence level.

Results and Discussion

Bioretention Box Studies. Box prototype studies were conducted in the laboratory to simulate the behavior of actual bioretention facilities under different runoff physical and chemical characteristics. These conditions were varied individually and the extent of their influence on the overall performance of bioretention was assessed and compared to the results obtained from "standard conditions", which are described in the literature by Davis et al. (2001b). In all cases, metal concentrations varied little throughout the duration of a single experiment; no temporal trends were apparent. Metal removal occurs via adsorption to the surface mulch layer and to the soil media as the water infiltrates through the bioretention cell (Davis et al., 2001b).

Duration and Flowrate (Intensity) Effects. Experiments were carried out to assess the influence of event hydrologic considerations on bioretention performance. First, studies were completed for a 3-hour duration, one-half of that for the standard condition. A head of ponded water built up to a maximum of 5 to 9 cm in the small box during the 3-hour duration compared with 6 to 12 cm for the 6-hour standard duration. Results for the three metals and, for comparison, those from the standard 6-hour duration studies are presented in Table 2. Effluent concentrations for all three metals from the lower ports were essentially identical for both durations (approximately 3 μg/L for copper and below quantitation limits for

lead and zinc). The lead and zinc concentrations from the upper ports were statistically higher based on the Student's t test, but still low, with excellent removal.

A slight improvement was noted with effluent levels and metal removal percentages from the upper ports when the flowrate was reduced to one-half (2 cm/h) of the normal rate (Table 2). The lead (in both boxes) and zinc (in the large box) levels were at or below quantitation, whereas they were somewhat larger under the standard flow. Under the half-flow conditions, head buildup as high as 3.5 cm occurred during the experiments with the small box. The maximum head in the large box was 7.0 cm, compared with 18 cm at the standard condition flowrate. Lower port data indicated excellent metal treatment and removal. The copper concentration was statistically lower than that from the standard experiments for both boxes.

These results are not surprising. The lower duration and flowrate provide little perturbation to the physical and chemical processes that are occurring as the water infiltrates through the boxes. Adequate reaction time is provided for metal attenuation under the standard conditions, and effluent metals remain low. The treatment efficiencies are just slightly better for these smaller events.

In further evaluating metal removal in these systems, mass balances can be calculated by monitoring input mass (M_I) over the runoff application time (T_d) as follows:

$$M_I = Q_I C_I T_d \tag{1}$$

where Q_I and C_I are the input flowrate (L/s) and representative metal concentration (μg/L), respectively (both constant). The metal mass output (M_O) is found as

Flowrate halved (2 cm/h)			12-Hour duration			Flowrate doubled (8.1 cm/h)		
Cu (µg/L)	Pb (µg/L)	Zn (µg/L)	Cu (µg/L)	Pb (µg/L)	Zn (µg/L)	Cu (µg/L)	Pb (µg/L)	Zn (µg/L)
98 ± 38	58 ± 16	640 ± 40	74 ± 23	50 ± 45	630 ± 32	93 ± 15	38 ± 14	650 ± 20
6.8 ± 3.4[b]	2.0 ± 1.0[b]	46 ± 20	9.4 ± 4.0[b]	2.7 ± 2.3	77 ± 44[b]	10 ± 5.8	<2[b]	78 ± 31[b]
2.3 ± 1.3[b]	<2	<25	4.3 ± 1.9	<2	<25	4.2 ± 2.6	<2	<25
93 ± 5	>97	93 ± 4	87 ± 6	95 ± 4	88 ± 7	89 ± 7	>95	88 ± 5
97 ± 2	>97	>96	94 ± 3	>96	96 ± 5	96 ± 3	>95	>96
99	>99	>98	98, 94[c]	99, 95[c]	99, 95[c]	98, 66[c]	>99, 67[c]	99, 67[c]
83 ± 26	59 ± 49	550 ± 44	–	–	–	76 ± 51	81 ± 69	570 ± 52
6.9 ± 2.1	<2	<25	–	–	–	12 ± 6.7[b]	3.1 ± 1.4	84 ± 33
4.7 ± 0.9	<2	<25	–	–	–	6.9 ± 3.7	4.1 ± 2.0[b]	<25
3.3 ± 1.1[b]	<2	<25	–	–	–	5.2 ± 4.0	<2	<25
91 ± 3	>97	>95	–	–	–	87 ± 6	96 ± 2	85 ± 6
94 ± 1	>97	>95	–	–	–	90 ± 5	95 ± 3	>96
96 ± 1	>97	>95	–	–	–	93 ± 6	>98	>96
>99	>99	>99	–	–	–	99, 78[c]	>99, 79[c]	>99, 79[c]

[a] U = upper ports, M = middle ports, and L = lower ports.

[b] t test indicates significantly different from standard conditions at 95% confidence level.

[c] Second number considers mass lost due to "bypass" in experiments where head was greater than approximately 16 cm; see text for details.

$$M_o = \sum_{i}^{n} \sum_{0}^{T_E} Q(i, t)C(i, t)\Delta t \qquad (2)$$

where the product of effluent flowrate (L/s), metal concentration (µg/L), and time (s) increment is summed over the duration of the effluent flow (T_E) for each lower outlet (i) summed over the number of outlets in the bioretention box (n). The mass lost from upper sampling ports is negligible as they were opened only for a few seconds for sampling.

In all of the small box studies presented here, collected volume drained through the boxes ranged from 19 to 99%, depending on flow and duration conditions, with 63% being typical; the collected volume drained through the large box was always less than 30%. The remainder of the input water was held by the bioretention media and was ultimately lost through evapotranspiration. As a result, the total metal mass leaving the boxes was even lower than that indicated by the removals calculated using concentration differences. At low flowrate and duration, mass removals were 98% or greater for all three metals (Table 2).

In the 12-hour duration studies, the head increased to 15.5 cm in one small box experiment, the maximum value allowable for this box. This occurred 7.5 hours into the test, whereby the flowrate to the test box was decreased to maintain the head at this level, specifically from 4.1 to 2.7 cm/h for the remaining 4.5 hours. This procedure simulates a long-duration storm event that causes pooling in a bioretention facility. Any runoff that exceeds the pool upper level would bypass the bioretention treatment. The other two experiments in the 12-hour duration study did not result in head buildup over the 15.5-cm limit.

Metal results based on effluent concentrations do not show any significant effects from the longer duration. The zinc concentration from the upper port is statistically higher (77 ± 44 µg/L compared with 45 ± 13 µg/L), but the upper port copper level is statistically lower. Regardless, in all duration studies, metal concentrations leaving the lower ports are low (i.e., approximately 4 µg/L for copper, less than 2 µg/L for lead, and near 25 µg/L for zinc). In all cases, the removal is 94% or higher.

In the mass balance analysis for these systems, just the added water is considered first, and with some of the water held in the system, the total mass removal is 98% or greater. A true mass balance for the long duration, however, must consider the metal mass lost due to the "bypass" (1.4 cm/h for 4.5 hours during the one experiment). In this case, the mass removal drops slightly to 94 to 95%.

At the 8.1 cm/h doubled flowrate, the head built up to greater than the allowed value in all cases. When the limit was reached, the flowrate was again decreased to keep the head constant at this upper level. The maximum head was 14 to 16 cm, and the time to reach this value ranged from 2.25 to 6 hours. After reaching the limit, the flowrate was reduced to approximately 1.1 cm/h in the small boxes and 2 cm/h in the large box. Little noticeable effect was apparent in effluent concentrations from the higher flows and resulting higher head. As in the long duration study, high zinc concentration was noted in the effluent of the upper ports of the small box. Higher copper and lead concentrations were noted from two ports in the large box. Evaluating mass balances on treated flow only, the mass removal is excellent (98%). Again, however, considering the flow reduction as producing an influent bypass and

Table 3—Summary of metal removal for boxes at different pH and metal concentrations.

	pH 6			pH 8			Double concentration			Half concentration		
	Cu (μg/L)	Pb (μg/L)	Zn (μg/L)	Cu (μg/L)	Pb (μg/L)	Zn (μg/L)	Cu (μg/L)	Pb (μg/L)	Zn (μg/L)	Cu (μg/L)	Pb (μg/L)	Zn (μg/L)
I. Small box[a]												
Influent Average ± standard deviation	47 ± 17	91 ± 62	580 ± 61	84 ± 15	64 ± 61	530 ± 77	160 ± 13	104 ± 79	1290 ± 95	41 ± 11	32 ± 20	320 ± 24
U	8.4 ± 3.7[b]	2.7 ± 1.6	54 ± 23	9.5 ± 1.7	2.4 ± 0.8	38 ± 13	9.7 ± 2.7	<2[b]	53 ± 25	6.2 ± 2.1[b]	2.3 ± 2.2	43 ± 30
L	3.2 ± 3.7	<2	<25	4.2 ± 1.8	<2	<25	3.8 ± 1.3	<2	<25	2.8 ± 1.1[b]	<2	<25
Removal (%)												
U	82 ± 8	97 ± 2	91 ± 4	89 ± 2	97 ± 2	94 ± 4	94 ± 2	>98	96 ± 2	85 ± 5	93 ± 6	87 ± 10
L	93 ± 8	>97	>96	95 ± 2	>97	>95	98 ± 1	>98	>98	93 ± 3	>94	>92
Mass removal (%)	97	>99	>99	99	>99	>99	99	>99	>99	97	99	99
II. Large box[a]												
Influent Average ± standard deviation	–	–	–	–	–	–	–	–	–	38 ± 19	41 ± 36	260 ± 68
U	–	–	–	–	–	–	–	–	–	7.4 ± 1.7	<2	50 ± 12
M	–	–	–	–	–	–	–	–	–	5.9 ± 3.3	<2	<25
L	–	–	–	–	–	–	–	–	–	2.9 ± 2.5	<2	<25
Removal (%)												
U	–	–	–	–	–	–	–	–	–	81 ± 5	>95	81 ± 5
M	–	–	–	–	–	–	–	–	–	85 ± 9	>95	>90
L	–	–	–	–	–	–	–	–	–	92 ± 6	>95	>90
Mass removal (%)	–	–	–	–	–	–	–	–	–	98	>99	99

[a] U = upper ports, M = middle ports, and L = lower ports.
[b] t test indicates significantly different from standard conditions at 95% confidence level.

corresponding lost pollutant, the total metal mass capture is reduced to 66 to 79%.

Overall, several conclusions can be derived from both the duration and flowrate (intensity) studies. First, the removal of metals is somewhat dependent on the flowrate and duration, which control the height of the pool above the bioretention cell. This effect, however, is generally noticeable only at the upper portions of the cell, where removal is better at low flows and degrades at the higher flows. Deeper in the facility, the removals are unaffected by the flow variations. Regardless, the lower-drain metal removals can still be considered as excellent, with copper, lead, and zinc levels of approximately 2 to 5 μg/L, less than 2 μg/L, and less than 25 μg/L, respectively. A significant concern here is the buildup of head above the point of system bypass. At the double flowrate, the system treated the full flow only for approximately one-half of the 6-hour duration, whereby the input flowrate was decreased to approximately one-fourth of the target value, overall treating only approximately 68% of the design input volume. The total mass removals for the practice, which are considerably less than those calculated based only on infiltrated flow, must consider this bypass. This issue of bypass becomes less important if the facility is treating a flow with a strong first flush, as opposed to the constant pollutant concentration delivered here. The permeability of the soil and resulting infiltration rate was not a controlled variable in these studies. A higher permeability media with a strong metal binding capacity could alleviate concerns of excessive pooling and bypass.

Runoff pH and Metal Concentration Effects. As expected with changing the runoff chemistry, head buildup and fall were similar to those observed for the standard conditions. Two replicate experiments were each performed where the pH of the applied runoff to the bioretention cells was fixed at 6 and at 8. At these input pH values, the metal concentration and removal results do not differ greatly from the standard studies at pH 7 (Table 3). Only the upper-port copper level difference is significant. At the bottom sampling points, the effluent copper concentrations averaged 3.2 and 4.2 μg/L, while those for lead and zinc were always below their respective detection limits. Therefore, despite variations in runoff pH, output pollutant levels remained unchanged and low. Metal adsorption onto soils is typically highly dependent on pH, and small changes in pH potentially can have significant ramifications on metal attenuation. The buffering capacity of the soil, however, negates significant effects from influent pH variation.

With changes in the input metal concentrations, both absolute and relative removals must be examined when compared with the standard conditions as these will be different. At one-half of the concentration, effluent copper levels were slightly lower, but percent removals were somewhat worse. For both input concentrations, the lower-port lead and zinc concentrations were below detection limits. Accordingly, the bounds for percent removals are somewhat greater at the higher input levels. This again demonstrates the ability of these facilities to resist input variability through the vertical flow and depth pathway. Evaluating mass balances, total mass removals were again all greater than 97%, and no flow was bypassed (Table 3).

Field Study Results. *Greenbelt Field Experiment.* The occurrence of flow 15 minutes after runoff application indicates a high
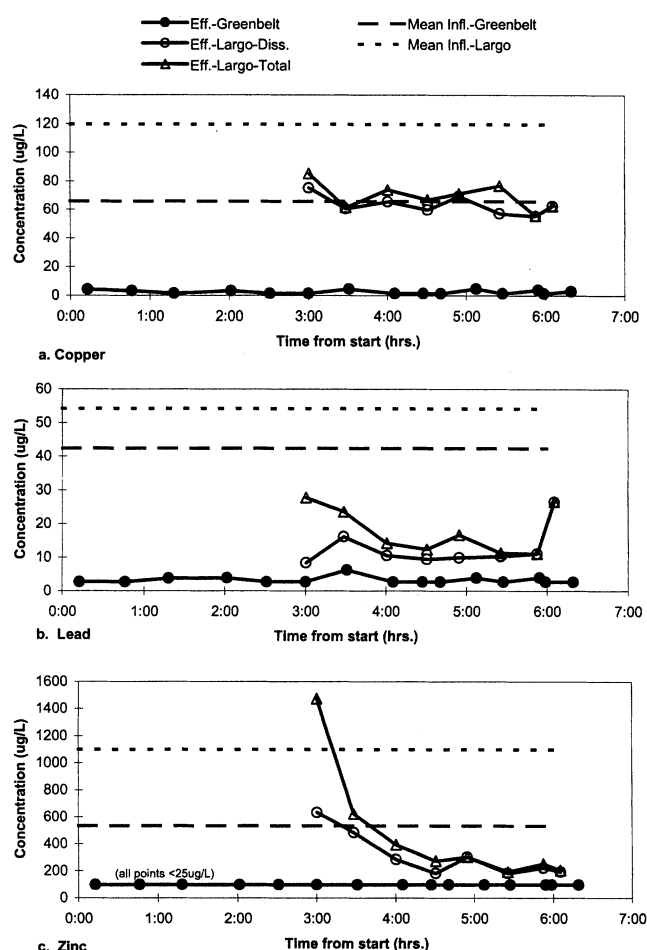
Figure 2—Field bioretention during synthetic runoff application: (a) copper, (b) lead, and (c) zinc.

Greenbelt. Although the input concentration for copper and zinc was higher than at Greenbelt, the effluent concentration was much higher. Total metal was always greater than dissolved metal, although the difference was usually slight. Total lead was significantly removed at a rate of approximately 70 ± 23%; total copper was removed to a lesser extent (43 ± 11%). Zinc was also reduced; Figure 1c, however, shows that the first sample unexplainably had a total effluent zinc concentration higher than the input. A slight trend of improved removal with time was apparent, with an average removal of 64 ± 42%. The removals were 5 to 14% better for the dissolved metals. For all three metals, no particulate metal was input to the system and most of the effluent metal was dissolved.

Removals for all three metals from the Largo facility were less than those found from the study at Greenbelt. The immediate factor to attribute this to is the difference in the makeup of the bioretention infiltration media. The facility at Largo was built with construction sand, topsoil, and leaf compost, while the Greenbelt facility contains a higher soil and fines fraction. Laboratory and pilot studies have implicated the surface mulch layer as the most important component of the bioretention facility for metals removal (Davis et al., 2001b). The Largo facility has a well-maintained mulch layer that should have been efficient in metals removal, although this was not observed. Another difference between the facilities is their age. Also, Greenbelt had a full growth of grasses, the roots of which could have promoted metal attenuation. In addition, the facility age and maturity may provide more efficient metal uptake pathways. Artifacts resulting from having to collect the Largo samples from the storm drain joints, instead of having the runoff exit from the perforated underdrain, are not entirely known. The travel path to the storm drain was longer than that from the underdrain, which may suggest that this water is receiving better treatment. Interactions with the concrete and other materials in the storm drain, however, may have contributed low levels of metals.

Bioretention Depth Effects. Results from the two field studies can be compared with the "standard condition" pilot-scale bioretention box experiments presented by Davis et al. (2001b) and reproduced in Table 2. Combining the effluent data from the two field and two box experiments yields pollutant removals at several different bioretention depths. The three different experimental scales can be compared, and specific examination of the pollutant removal efficiencies as a function of bioretention depth is possible

infiltration rate for this facility. Initially, the flow was mostly coming from cracks in the manhole concrete around the PVC pipe, but later flow also occurred through the pipe itself. The surface of the bioretention area became completely wet, but no pooling occurred throughout the entire application period. Approximately 15 minutes after the termination of the experiment, the drainage from the PVC pipe slowed; by one-half hour it was reduced to a trickle, and by 1 hour flow was not noticeable.

Metals results from this experiment are shown in Figure 2. An average for three input concentrations is shown for each of the three metals. The effluent metal concentrations were essentially constant and the three metals were all nearly totally removed by the bioretention facility. A summary of all field results is given in Table 4. The copper and lead concentrations in the effluent were less than or near instrument detection limits (2 μg/L), demonstrating removals of 97 ± 2% and greater than 95%, respectively. All of the zinc concentrations were below the detection limit, for a removal rate greater than 95%. The total effluent water volume was only a small fraction of the input because of the water-holding capacity of the soil and, most likely, lateral movement. Consequently, mass balances were not calculated.

Largo Field Experiment. Largo data are also presented in Figure 2 and summarized in Table 4. Both copper and lead concentrations were reduced by the treatment, but not to the extent found at

Table 4—Metal pollutant removal summary for field studies.

	Cu (μg/L)	Pb (μg/L)	Zn (μg/L)
Greenbelt field study			
Input	66 ± 32	42 ± 35	530 ± 72
Effluent mean ± standard deviation	2 ± 1	<2[a]	<25[a]
Removal (%)	97 ± 2	>95	>95
Largo field study			
Input	120 ± 27	54 ± 9.4	1100 ± 20
Effluent mean ± standard deviation	69 ± 9.4	16 ± 7	390 ± 440
Removal (%)	43 ± 11	70 ± 23	64 ± 42

[a] < Indicates values below the listed detection limit.

▲ Small Box   ● Large Box   ☐ Greenbelt   ◇ Largo

a. Copper   Bioretention Depth (cm)

b. Lead   Bioretention Depth (cm)
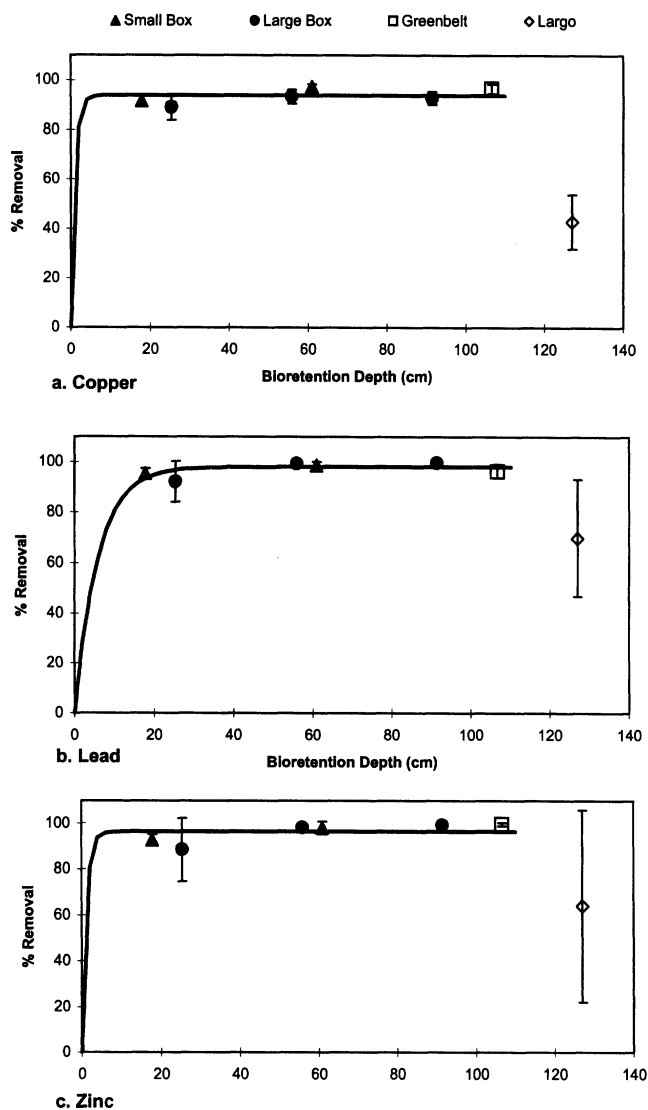

c. Zinc

Figure 3—Pollutant removals as a function of bioretention depth (data for boxes from Davis et al. [2001b]): (a) copper, (b) lead, and (c) zinc.

(Figure 3). Error bars represent the standard deviation (plus or minus) for data collected.

Results show excellent agreement among the various laboratory experiments. This was expected because the same soil and mulch matrix was used in each experiment. In addition, this agreement extended to include the Greenbelt field data, even though the bioretention media were not the same. Metal removals were all greater than 90%, and variations were small. Most of the metals were removed with just 20 cm of bioretention depth, which includes the mulch layer on the surface. Results from the Largo study, however, did not demonstrate the same degree of metals removal. As previously discussed, several differences between the Largo and Greenbelt facilities could have been responsible for the capture efficiency variations.

Consideration of Long-Term Metal Accumulation Issues. Capturing pollutants by a stormwater BMP fundamentally alters existing pollutant transport pathways. By using a BMP for metals capture, the metals are kept in the uplands, as opposed to becoming

diffuse pollution that is dispersed downstream. However, this capture creates a pollutant "depot" that has ownership.

A large hurdle in the development of an appropriate approach to the design, operation, and maintenance of bioretention and other similar practices is how to address accumulated heavy metals over many years of successful operation, for example whether these facilities should be frequently maintained (at relatively high costs) when metal accumulations are low; if a significant maintenance endeavor should be initiated every few years to remove more (and likely more contaminated) material; the role (if any) that vegetative uptake plays in removing trapped metals from these facilities; and if bioretention media can be modified to capture and render metals nonavailable. Best management practice "owners" require this fundamental information on pollutant fate to appropriately design and manage these facilities.

Cumulative metal loadings to stormwater infiltration BMPs such as bioretention can be gauged by estimating operating parameters and conditions. Here, a sample calculation is presented to examine metal buildup. The input information necessary includes runoff volume, which is estimated using 90 cm/a of rainfall, runoff volume of 90% of rainfalls (c = 0.9), and a 30:1 concentration of drainage area to BMP area. The result is 24 300 L runoff/m^2 of BMP/a. For a 20-year facility lifetime, this gives 486 000 L/m^2 = 4.86 × 10^9 L/ha. Using typical cadmium, copper, lead, and zinc concentrations in urban and roadway runoff, and assuming that all metals are captured (as was previously demonstrated, cadmium is assumed to be similarly removed), a lifetime value of accumulated metal is found (Table 5).

One approach to examine the lifetime metal burdens is by comparison to the cumulative metal loadings permitted on U.S. lands through the application of wastewater biosolids, similar to the analysis for roadway metals accumulation done by Barrett et al. (1998). After 20 years, cadmium, lead, and zinc accumulations reach or exceed regulatory limits for biosolids application (U.S.

Table 5—Estimation of lifetime accumulated heavy metal levels in infiltration BMPs (See text for details).

	Cadmium	Copper	Lead	Zinc
Typical concentration in urban runoff (μg/L)	8	80	75	700
20-Year lifetime accumulated metals (kg/ha)	39	389	365	3400
Cumulative loading, regulatory limits[a] (kg/ha)	39	1500	300	2800
Years of accumulation before exceeding regulatory limits[a]	20	77	16	16
Estimation of TCLP extracts of infiltration BMP media				
20-Year lifetime accumulated metals in soil/media (mg/kg)	8.0	80	75	700
Max. possible concentration in TCLP extract (20:1 liquid:solids) (mg/L)	0.4	4	3.8	35
Allowable concentration in TCLP extract (mg/L)	1	No limit	5	No limit
Years of accumulation before exceeding TCLP levels	50	–	26	–

[a] Part 503 biosolids regulations (U.S. EPA, 1993).

EPA, 1993). The time required for metal accumulations to reach these limits are 20, 77, 16, and 16 years for cadmium, copper, lead, and zinc, respectively. Lead and zinc are the limiting metals and, at the regulated values, metal levels may present a health risk. Metal buildup should be halted and facility reconstruction should be addressed.

With additional information and assumptions, the media can also be evaluated with respect to hazardous waste classification criteria based on allowable toxicity characteristic leaching procedure (TCLP) concentrations (Table 5). It is assumed that the depth of metal accumulation in facility media is 0.305 m (1 ft) and the bulk specific weight of soil and media in a facility that accumulates metal is 1600 kg/m³ (100 lb/cu ft). Only cadmium and lead have TCLP limits. After 20 years, accumulated levels of these two metals approach, but do not exceed, the allowable TCLP extraction levels. The time required to reach the TCLP limits are 50 years for cadmium and 26 years for lead. This example, however, assumes that all metals are readily available and will be extracted in the TCLP; it is, thus, conservative. Greater metal accumulation could occur before TCLP limits are reached.

Overall, these calculations suggest that accumulated metal levels should not be an issue within the short term. Over a 20-year lifetime, however, these metal buildups may present environmental concerns. Studies should be completed to confirm these estimates and appropriate management strategies should be developed.

Environmental Significance: Heavy Metals and Bioretention

Bioretention is efficient at removing heavy metals from infiltrating stormwater. Metal concentrations exiting the facility are low (i.e., on the order of a few micrograms per liter or less for copper and lead and maybe somewhat more for zinc). Bioretention is also resilient to fluctuations in infiltration flowrate because of intensity and duration effects as well as variations in water pH and metal concentrations. Efficient removal of dissolved metals over a wide range of conditions has been documented. An efficiency decline is seen at the highest flowrates and concentrations, but only from upper ports in the cells. The facility depth is sufficient to allow effective removal by the time the flow reaches the appropriate discharge point. It is important to minimize facility bypass at high flows, which can directly discharge pollutants with no treatment. Therefore, permeability that is as high as is reasonable should be used in the cell.

One field study, while demonstrating good (43 to 70%) removal of copper, lead, and zinc, did not approach the removal found in the other field study (greater than 95%). Several factors may have contributed to this difference including differences in bioretention media, plant density, and facility age. For drainage areas with a focus on heavy metals removal, such as commercial or industrial sites, a shallow bioretention facility with a significant mulch layer is recommended for effective removal of metals from stormwater. A minimum total depth of 30 cm may be required to properly support plant growth.

Mass balance considerations suggest that metal accumulations in bioretention should not be a significant issue for many years. After approximately 15 to 20 years, metals may accumulate to levels where ecosystem risks may become important. However, appropriate technology to remove metals through periodic cutting and removal of plant material and mulch as routine maintenance should be considered. Significant work has been done recently

demonstrating the ability of vegetation to hyperaccumulate heavy metals (Brown et al., 1995; Ebbs and Kochian, 1998; Sarret et al., 2001; Wu et al., 1999). The growth and harvesting of these plants could be exploited as a mechanism for the continuous removal of metals from bioretention facilities. Another possibility is to investigate soil additives that can bind metals and render them nonbioavailable (Brown et al., 1997, 1998; Li et al., 2000). Long-term investigations are necessary to evaluate the fate and transport of pollutants held within the facilities, to optimize the function of the vegetation, and to determine ultimate capacities for metal uptake mechanisms.

Summary and Conclusions

Controlled studies using laboratory boxes and existing facilities have demonstrated that bioretention is effective at removing heavy metals from infiltrating water. Removals of lead, copper, and zinc were excellent, reaching close to 100% for all metals under most conditions based on both concentration and total mass. Effluent copper and lead levels were mostly less than 5 μg/L, and zinc was less than 25 μg/L. Somewhat less removal was noted for shallow bioretention depths (less than 30 cm). Variations in runoff pH, duration, intensity, and pollutant concentrations all had minimal effect on removal. Of concern is minimizing runoff bypass of the bioretention treatment and the long-term accumulation of metals in the facilities.

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